Journal of Athletic Training 2010;45(3):259–264

www.nata.org/jat

original research

A Description of Shock Attenuation for Children Running

John A. Mercer, PhD, FACSM; Janet S. Dufek, PhD, FACSM; Brent C. Mangus, EdD, ATC; Mack D. Rubley, PhD, LAT, ATC, CSCS*D; Kunal Bhanot, MS, PT; Jennifer M. Aldridge, BS

Department of Kinesiology and Nutrition Sciences, University of Nevada, Las Vegas. Dr Mangus is now at Texas A&M University–Commerce.

Context: A growing number of children are participating in organized sport activities, resulting in a concomitant increase in lower extremity injuries. Little is known about the impact generated when children are running or how this impact is attenuated in child runners.

Objective: To describe shock attenuation characteristics for children running at different speeds on a treadmill and at a single speed over ground.

Design: Prospective cohort study.

Setting: Biomechanics laboratory.

Patients or Other Participants: Eleven boys (age = 10.5 ± 0.9 years, height = 143.7 ± 8.3 cm, mass = 39.4 ± 10.9 kg) and 7 girls (age = 9.9 ± 1.1 years, height = 136.2 ± 7.7 cm, mass = 35.1 ± 9.6 kg) participated.

Intervention(s): Participants completed 4 running conditions, including 3 treadmill (TM) running speeds (preferred, fast [0.5 m/s more than preferred], and slow [0.5 m/s less than preferred]) and 1 overground (OG) running speed.

Main Outcome Measure(s): We measured leg peak impact acceleration (LgPk), head peak impact acceleration (HdPk), and shock attenuation (ratio of LgPk to HdPk).

Results: Shock attenuation ($F_{2,16} = 4.80$, $P = .01$) was influenced by the interaction of speed and sex. Shock attenuation increased across speeds (slow, preferred, fast) for boys ($P < .05$) but not for girls ($P > .05$). Both LgPk ($F_{1,16} = 5.04$, $P = .04$) and HdPk ($F_{1,16} = 6.04$, $P = .03$) were different across speeds, and both were greater for girls than for boys. None of the dependent variables were influenced by the interaction of setting (TM, OG) and sex ($P \geq .05$). Shock attenuation ($F_{1,16} = 33.51$, $P < .001$) and LgPk ($F_{1,16} = 31.54$, $P < .001$) were different between TM and OG, and each was greater when running OG than on the TM, regardless of sex.

Conclusions: Shock attenuation was between 66% and 76% for children running under a variety of conditions. Girls had greater peak impact accelerations at the leg and head levels than boys but achieved similar shock attenuation. We do not know how these shock attenuation characteristics are related to overuse injuries.

Key Words: boy and girl runners, impact, lower extremity injuries

Key Points

- Children attenuated different amounts of shock while running on a treadmill and over ground.
- Leg and head peak impact accelerations were greater in girls than in boys.
- Boys and girls achieved similar shock attenuation levels under various running conditions.
- We do not know the mechanism for shock attenuation in child runners.
- When developing rehabilitation programs for children, the practitioner should consider that shock attenuation varies across running speeds and between treadmill and overground running.

Running is a primary component of many organized games and sport activities, including soccer, football, basketball, and tennis, in which a growing number of boys and girls are now participating at a young age. Stanitski[1] estimated that 50% of all boys and 25% of all girls aged 8 to 16 years in the United States participate in some form of organized, competitive sport. Marsh and Daigneault[2] estimated that 45 million children participate in organized sports programs each year. DiFiori[3] reported that many of the children between the ages of 5 and 17 years who participate in organized athletic programs train and compete on a year-round basis, often specializing in a single sport. The increasing number of children participating in organized sports has produced a concomitant increase in the number of injuries they experience,[4] ranging from overuse injuries[5] to fractures.[6,7]

A wealth of research[8–10] on how the repetitive loading nature of running is linked to overuse injuries exists, and this research focuses on the adult runner. Given that children may also develop overuse injuries, much like adults, when they participate in running activities that require endurance and repetitive stresses,[11,12] it is important to understand the impact characteristics of a child running.

Shock attenuation is a measure used to understand impact characteristics because it represents the process of reducing the impact that results from the collision between the foot and ground during running.[13–19] Shock attenuation is accomplished by passive structures (eg, bone) absorbing impact energy and by active movements, such as knee and hip flexion during impact. For adult runners, shock attenuation is affected by running speed,[13,14] stride length (SL),[15–17] and fatigue,[18,19] for example. To date, however, no one has described shock attenuation in boy and girl runners, despite recommendations in the literature[20] to seek this type of information in an attempt to understand injuries to children. Therefore, the purpose of our study was to document shock attenuation for boys and girls while they were running at different speeds on a treadmill (TM) and at a single speed over ground (OG). Our intent was to establish a broad baseline description of shock attenuation for children.

METHODS

Participants

Eleven boys (age = 10.5 ± 0.9 years, height = 143.7 ± 8.3 cm, mass = 39.4 ± 10.9 kg) and 7 girls (age = 9.9 ± 1.1 years, height = 136.2 ± 7.7 cm, mass = 35.1 ± 9.6 kg) participated. All children were given instructions and time to practice running both on a TM and OG in the laboratory until they were comfortable with the activities. During this phase of the test, participants were encouraged to walk and run at different speeds. Participants were only included in the study if they could demonstrate comfortable gait patterns on the TM while not holding onto the rails. Participants completed all running conditions while wearing their own shoes.

All participants gave assent to participate, and their parents provided written consent. The study was approved by the institutional review board at the affiliated university.

Instrumentation

After practice, children were instrumented with 2 lightweight uniaxial piezoelectric accelerometers (1000 Hz; PCB Piezotronics Inc, Depew, NY), following procedures used for adult runners.[13,17,18] One accelerometer was mounted on a piece of balsa wood, aligned vertically on the distal anterior portion of the tibia, and secured snugly with stretchable bandage tape. The second accelerometer was attached to a headpiece, aligned vertically on the frontal portion of the child's forehead, and tightly secured around the child's head. Accelerometers were interfaced through a type 9865B 8-channel amplifier (Kistler Instrument Corp, Amherst, NY) to a data acquisition system using Bioware software (version 3.21; Kistler Instrument Corp). We used minimal instrumentation (2 accelerometers) and opted not to include motion capture instrumentation because its inclusion would increase the participant set-up and collection time and because we believed keeping collection time short was important when working with children.

Procedures

The participants completed 4 running conditions. The first 3 conditions were performed on a TM (model C966; Precor Inc, Woodinville, WA) and consisted of different running speeds based upon a preferred speed. A TM was used because most research on shock attenuation in adults has involved a TM and we wanted to follow that research model. We also used a TM because we could collect information on consecutive strides.

Before instrumenting a participant with the accelerometers, we determined the preferred speed by having him or her run on the TM. When comfortable, the participant was instructed to select a speed that he or she felt could be maintained for a 15-minute run. The tester (K.B. or J.M.A.) adjusted TM speed based upon participant feedback, with the TM speed display concealed from the participant's view. After a 2-minute to 5-minute period of speed adjustments, the final speed the participant selected was recorded. This procedure was repeated 3 times, and the preferred speed was calculated as the average of these 3 speeds.

After the preferred speed was identified, the participant was instrumented with the accelerometers. The first condition completed was at the preferred speed. The second condition completed was at a fast speed, which was 0.5 m/s greater than the preferred speed. The third condition completed was at a slow speed, which was 0.5 m/s less than the preferred speed. During each TM condition, the child ran for approximately 2 minutes at the given speed, with accelerometer data obtained for 45 seconds during the second minute of running. The fourth running condition (OG) was performed over a 20-m tile runway. Two infrared photocells were used to monitor running speed over the 3-m central portion of the runway. Children were instructed to run at the same speed as their previously determined preferred speed. A trial was accepted if their OG speed was within ±5% of the preferred speed recorded from their TM running. Ten acceptable OG running trials were obtained from each child runner. Rest was provided between trials (and conditions) as needed.

Data Analysis

Ten right-stance phase trials per participant-condition were identified and evaluated from both the TM and OG running conditions. Evaluation of the stance phase included recording the leg peak impact acceleration (LgPk) value and the head peak impact acceleration (HdPk) value during the support phase of running. With these data we computed shock attenuation, using the following formula:

$$\text{Shock attenuation} = [1 - (\text{HdPk}/\text{LgPk})] \times 100 \qquad (1)$$

Using this formula, when impact accelerations are similar at the head and leg levels, shock attenuation will have a low value, indicating that little impact has been attenuated. In contrast, when the impact acceleration at the leg level is large compared with the impact acceleration at the head level, shock attenuation will be large, indicating that more impact has been attenuated.

Stride length was computed for each trial by identifying the time at which LgPk occurred between consecutive right-side foot strikes. The inverse of this time represents stride frequency (SF). Knowing SF and running velocity, SL was calculated using the following formula: Velocity = SF × SL.

A statistical power analysis was conducted a priori for the dependent variable of shock attenuation, using exploratory child data obtained previously in our laboratory. The assumption of equal variances was embraced. Using the observed common SD of 1.5 between partici-

Table. Descriptive Data (Mean ± SD) by Sex, Speed, and Setting Conditions for Shock Attenuation, Leg Peak Impact Accelerations, Head Peak Impact Accelerations, and Stride Length While Running at Different Speeds on the Treadmill and a Single Speed Over Ground

Condition	Sex	Speed, m/s	Shock Attenuation,[a] %	Leg Peak Impact Accelerations,[b] *g*	Head Peak Impact Accelerations,[b] *g*	Stride Length,[b,c] m
Slow treadmill	Girls	1.68 ± 0.45	74.1 ± 10.1	5.38 ± 1.62	1.24 ± 0.33	1.09 ± 0.28
	Boys	2.18 ± 0.31	66.6 ± 8.8	3.45 ± 1.25	1.02 ± 0.22	1.50 ± 0.16
Preferred treadmill	Girls	2.11 ± 0.45	69.9 ± 9.1	5.71 ± 2.28	1.57 ± 0.54	1.33 ± 0.26
	Boys	2.67 ± 0.30	71.7 ± 6.9	4.09 ± 1.31	1.07 ± 0.21	1.58 ± 0.23
Fast treadmill	Girls	2.54 ± 0.51	76.2 ± 9.3	7.48 ± 3.07	1.58 ± 0.44	1.56 ± 0.27
	Boys	3.18 ± 0.30	73.5 ± 6.6	5.53 ± 1.77	1.32 ± 0.22	1.60 ± 0.37
Preferred overground	Girls	2.29 ± 0.40	81.7 ± 6.1	8.78 ± 2.82	1.46 ± 0.43	1.48 ± 0.29
	Boys	2.71 ± 0.30	81.1 ± 5.1	5.51 ± 1.71	0.98 ± 0.29	1.69 ± 0.25

[a] Shock attenuation was not different between sexes, although girls had greater leg peak impact accelerations and head peak impact accelerations values than boys.
[b] Different between sexes ($P < .05$).
[c] Different between sexes at slow and preferred treadmill speeds ($P < .05$) and tendency to be shorter for girls than boys during overground versus treadmill ($P = .08$).

pants, a desired statistical power of 90%, and a nondirectional hypothesis, we calculated that 9.8 participants would be needed for each group. We made another calculation in which the common SD was increased to 1.75 with a desired statistical power of 75%. This resulted in a sample size of 8.9. Based upon these calculations, we determined that 9 participants per group would provide statistical power at a minimum of 75% power. Our sample size for one group (girls) fell below this criterion (n = 7) as a result of instrumentation malfunction, whereas our other group (boys) exceeded this sample size criterion (n = 11).

The main dependent variable was shock attenuation. Because shock attenuation is determined by the ratio of LgPk to HdPk, these measures were also analyzed individually. Finally, we also analyzed SL because this is a basic kinematic descriptor of gait and has been shown[13,17] to provide insight into the mechanism of shock attenuation in adult runners.

Each dependent variable (shock attenuation, LgPk, HdPk, SL) was examined using 2 analyses: (1) 2-way (sex by speed) mixed-model analyses of variance (ANOVAs) using data collected during the TM conditions only and (2) 2-way (sex by setting) repeated-measures ANOVAs for the matched-speed (preferred) running conditions to address possible sex and running setting (TM, OG) effects. All statistical tests were conducted using Statistical Analysis Software (version 8.2; SAS Institute Inc, Cary, NC) with the α level set at .05. We planned a priori to compare dependent variables at each speed between boys and girls and between speeds for boys and for girls using Scheffé post hoc *t* testing. When interactions were present, either dependent or independent *t* tests (based on whether the comparison was within or between subjects) were used to identify the source of the interaction.

RESULTS

A part of the experiment consisted of matching preferred running speed on the TM and OG. We found no differences in the preferred speed used during TM and OG for either sex ($F_{1,16} = 3.38$, $P = .8$). However, the preferred speed was faster for boys (TM = 2.69 ± 0.31 m/s, OG = 2.71 ± 0.30 m/s) than for girls (TM = 2.11 ± 0.45 m/s, OG = 2.29 ± 0.40 m/s) ($F_{1,16} = 9.65$, $P = .007$) (Table).

Speed by Sex

The mean and SD data for each dependent variable are presented in the Table. Shock attenuation was influenced by the interaction of speed and sex ($F_{2,16} = 4.80$, $P = .01$). Using post hoc testing, we determined that shock attenuation was not different between girls and boys for any of the speed conditions ($P > .05$). We also determined that shock attenuation increased about 10% for each meter per second increase in speed for boys ($P < .05$). However, for girls, shock attenuation was not different between the slow and preferred speeds ($P > .05$) but was about 9% greater during the fast than during the preferred speed ($P < .05$).

We observed that neither HdPk ($F_{2,16} = 2.05$, $P = .15$) nor LgPk ($F_{2,16} = 0.18$, $P = .84$) was influenced by the interaction of speed and sex. Both HdPk ($F_{2,16} = 9.39$, $P < .001$) and LgPk ($F_{2,16} = 18.77$, $P < .001$) were influenced by the main effect for speed. They also were influenced by the main effect for sex; both HdPk ($F_{1,16} = 6.04$, $P = .03$) and LgPk ($F_{1,16} = 5.04$, $P = .04$) were greater for girls than for boys.

Stride length was influenced by the interaction of speed and sex ($F_{2,16} = 6.28$, $P = .005$). Using post hoc testing, we determined that SL was 38% shorter for girls than boys at the slow speed ($t_{16} = 3.98$, $P = .001$) and 19% shorter for girls than boys during the preferred speed ($t_{16} = 2.09$, $P = .05$), but SL was not different between sexes at the fast speed ($t_{16} = 0.25$, $P = .8$).

Setting by Sex

Shock attenuation ($F_{1,16} = 0.044$, $P = .52$), HdPk ($F_{1,16} = 0.01$, $P = .91$), LgPk ($F_{1,16} = 4.35$, $P = .05$), and SL ($F_{1,16} = 0.58$, $P = .46$) were not influenced by the interaction of setting and sex. Shock attenuation ($F_{1,16} = 33.51$, $P < .001$), LgPk ($F_{1,16} = 31.54$, $P < .001$), and SL ($F_{1,16} = 26.42$, $P < .001$) were each influenced by the main effect for setting; each was greater when running OG than when running on a TM, regardless of sex. Furthermore, regardless of setting, girls had a greater HdPk ($F_{1,16} = 10.45$, $P = .005$) and LgPk ($F_{1,16} = 7.86$, $P = .01$) than boys and tended to use a shorter SL ($F_{1,16} = 3.52$, $P = .08$).

DISCUSSION

The main purpose of our study was to describe shock attenuation characteristics for children running, because little is known about how children accommodate impact. To this end, we designed an experiment so we could describe shock attenuation characteristics for children (boys and girls) running at different speeds on a TM and at a single speed OG. The importance of shock attenuation is becoming better understood as it relates to injury resulting from impacts in both running and landing activities. How the body transmits and absorbs these impacts is part of shoe design, activity-related surface materials, and other factors designed to reduce athletic injury. Shoes generally are not manufactured similarly for adults and children. Information about how children attenuate shock may lead to more appropriate shoe design for children, which may result in diminished overuse injuries in children.

We are not aware of any shock attenuation data for children running in the literature with which to compare our results; Dufek et al[21] reported LgPk and HdPk for girls running but did not report on shock attenuation. However, the body of research on shock attenuation for adults running is robust and growing. For adult runners, shock attenuation typically ranges from about 80% to 90%, whereas typical peak impact accelerations range from around 2.0 to 11.3*g* at the leg and from 1.1 to 2.2*g* at the head.[13,15,17,18] In our study, the magnitude of shock attenuation tended to be lower for child runners (about 66%–76%) compared with published adult running data despite LgPk (3.3–10.5*g*) and HdPk (0.9–2.0*g*) ranges that were comparable with adult running data.[13,15,17,18] These results are similar to those for child runners[21] ($n = 11$ girls, 9.2 ± 1.9 years) who exhibited peak impact accelerations from about 4.9 to 6.1*g* at the leg and from 1.2 to 1.4*g* at the head level. Comparing the results to those of adults is complicated, because the variability of impact accelerations may be greater for children than adults[21] and because shock attenuation and LgPk are influenced by a variety of factors, including the primary factors of running speed and SL.[13,17] Our participants ran at preferred speeds ranging from 1.76 to 3.20 m/s and used SLs ranging from 1.0 to 2.1 m/stride. These values are lower than reported data from adult runners. For example, investigators of 2 studies[13,17] in which the relationship among shock attenuation, SL, and speed were investigated had participants run at speeds ranging from 3.2 to 6.4 m/s and from 3.3 to 4.4 m/s, with SL ranging from 3.40 to 3.68 m/stride and from 2.35 to 3.08 m/stride, respectively. Although our shock attenuation data for children seem to have lower values than data for adults, it is not clear if this is simply a result of slower speed or if differences exist in mechanisms for attenuating shock between children and adults. For example, we know that running economy is less optimal for child runners compared with adult runners[22] and that children run differently than adults,[21,23,24] and it may be that these movement differences may lead to different mechanisms of shock attenuation and possibly to differing injury mechanisms. Future research is needed to quantify the magnitude and to discern the importance of a lower shock attenuation in children versus adults. Additionally, it would be interesting to determine if shock attenuation is different between child recreational and child competitive athletes and if the injury rate in each group is related to the level of competition. Unfortunately, our experiment did not provide insight into this relationship, because our intent was to describe shock attenuation in children running. This baseline information will help future researchers determine some recommendations regarding injury prevention in children in high-intensity training programs.

In describing shock attenuation characteristics for children running, we believed that examining possible differences between sexes was important, because contemporary researchers[25,26] have documented differences in lower extremity injury rates between men and women. We used 2 basic experiments to address this question. In the first experiment, participants ran on a TM at different speeds, whereas in the second experiment, participants ran OG at the same preferred speed that was used on the TM. From these experiments, we determined that shock attenuation was not influenced by sex, although the girls demonstrated greater LgPk and HdPk values compared with the boys. Providing any directional hypotheses regarding the injury rates or differences between boys and girls is difficult at this time, because it is not clear why girls had greater impact accelerations than boys while running at the preferred speed. Given that the girls' preferred running speed was about 20% slower than the boys' preferred running speed and that the girls used a 19% shorter SL than the boys at the preferred speed, the girls' impacts (LgPk and HdPk) would be expected to be lower than the boys' impacts.[13,17] Because this was not the case, something other than speed and SL influenced the impact accelerations while running at the preferred speed. A possible explanation is that during running, the effective mass of girls was less than that of boys. Effective mass is used to represent the portion of a segmented or nonrigid body that is accelerated at a particular time. For example, when a person taps his or her finger on a table, the effective mass is the mass of the finger (or some portion thereof) versus the mass of the entire body, because only the finger is being accelerated. Similarly, during running, the effective mass being accelerated during the impact phase is some portion of the lower extremity. Derrick et al[27] demonstrated that impact accelerations were influenced by the effective mass being accelerated. Therefore, for a given force, as effective mass is reduced, acceleration increases. Effective mass of a runner can be influenced by running style. A greater understanding of effective mass might lead us to an understanding of injury potential in child and adult athletes. We were not able to discern if the effective mass was different between boys and girls in our study. However, running technique for boys and girls may have differed in such a way that effective mass was lower for girls. An alternative explanation is that the effective mass was influenced by anthropometric differences between groups. In our study, basic anthropometric measurements were different; the girl runners were on average younger (0.6 years) and shorter (7.5 cm) and had less mass (5.3 kg) than the boy runners. Further research is needed to determine if LgPk and HdPk differences were a result of running technique (eg, different knee flexion angle at contact between sexes) relative to physical maturation and skill. This could lead to a much greater understanding of the factor or factors leading to the avoidance of injury in running in both children and adults.

Our description of shock attenuation also included analyzing shock attenuation across speeds. We determined that shock attenuation increased as running speed increased for boys but not for girls. For boys, shock attenuation increased about 10% from slow to fast speeds, which was comparable to the change in speed. For girls, the shock attenuation achieved at the slow speed was not different from that achieved at the preferred speed, whereas shock attenuation was about 9% greater at the fast speed than at the preferred speed. Inspection of the components of shock attenuation led us to determine that LgPk and HdPk increased across speeds for both sexes; however, LgPk values were about 32% greater for girls than for boys at each speed, whereas HdPk values were about 25% greater for girls than for boys. The influence of speed on shock attenuation could not be accounted for by an analysis of SL. We do not know if the breakdown in the relationship between speed and shock attenuation is related to sex or if the relationship does not exist at slow running speeds. Further research is needed to explore the relationship between speed and shock attenuation for children running at faster speeds, as well as for adults running at slow speeds. This type of research should help investigators understand the risk of overuse injuries at different speeds by helping them understand the repetitive stresses realized at different speeds.

To determine the clinical relevance of differences in shock attenuation between individuals or groups (eg, boys versus girls, children versus adults), researchers could investigate this measure in injured and noninjured runners, for example. Our research should help to establish baseline measurements of shock attenuation in child runners.

Our final approach to describing shock attenuation characteristics for children running involved having children run on a TM and OG. By having children run at the same speed on a TM and OG, we determined that shock attenuation was greater during running OG than on a TM, regardless of sex. Furthermore, our inquiry relative to setting (TM, OG) effects determined that LgPk was greater during OG running than TM running across sexes. This result may simply reflect the function of the TM, which was a commercial-grade TM and constructed to attenuate impact to the runner. Nevertheless, another explanation for the differences is that participants ran differently during TM and OG conditions, given that participants used an ~6% longer SL during OG than TM, despite running at the same speed. The practitioner should be aware that impact characteristics and stride measures (eg, SL) are different when running on a TM than OG.

Limitations

Working with child participants is inherently different from working with adult participants; children are not miniature adults, and they run differently than adults.[21,23,24] Furthermore, in general, child participants have less running experience than adults. The experiment was planned to provide sufficient instruction and familiarization time for all participants, and children tended to pick up the task of running on a treadmill quickly. Nevertheless, the children's running experience level is a limitation, and we believe this may influence the magnitude of between-subjects and within-subjects variability of the self-selected running speed. We used this approach rather than setting specific target speeds per condition to avoid a situation in which children were running faster or slower than they may have wanted or were running faster than they were capable. The difference in speeds among participants (and among groups) likely resulted in increasing the variability of the dependent variables. Furthermore, it is not clear how much variability was introduced by having children run OG over a short distance. Another limitation of the study was that we did not control for the model of running shoe worn by children. For this study, we believed it was important to allow children to run in footwear with which they were accustomed instead of having them adapt to a new model of shoe. Future research is needed on how children's shoes (which may or may not be designed similar to adult shoes) influence impact characteristics.

Despite these limitations, our initial observations with this population revealed that children attenuated different amounts of shock while running on a TM and OG and that girls had greater LgPk and HdPk than boys, although girls ran more slowly and with shorter SLs. Despite these greater peak impact accelerations, girls achieved similar shock attenuation levels compared with boys under a variety of running conditions using shorter SLs. Unfortunately, we do not know the specific mechanism behind shock attenuation in child runners. For example, we do not know if passive structures (eg, bone) absorbed similar or differential impact energy among groups or conditions or if shock attenuation was accomplished primarily through active movements, such as knee and hip flexion. Nevertheless, taken together, it appears girls were exposed to greater and more frequent impact accelerations than boys. A possible explanation for these observations is that girls tended to run in a way that the effective mass was less than that of boys. Future research is needed to determine if these observations are contributing factors to overuse injuries. Finally, because shock attenuation did vary across speeds and between TM and OG running, the practitioner should take this into consideration when developing a rehabilitation program for children.

ACKNOWLEDGMENTS

This study was funded by research grant 905GP009 from the National Athletic Trainers' Association Research & Education Foundation.

REFERENCES

1. Stanitski CL. Common injuries in preadolescent and adolescent athletes: recommendations for prevention. *Sports Med.* 1989;7(1): 32–41.
2. Marsh JS, Daigneault JP. The young athlete. *Curr Opin Pediatr*. 1999;11(1):84–88.
3. DiFiori JP. Overuse injuries in young athletes: an overview. *Athl Ther Today*. 2002;7(6):25–29.
4. Junge A, Cheung K, Edwards T, Dvorak J. Injuries in youth amateur soccer and rugby players: comparison of incidence and characteristics. *Br J Sports Med.* 2004;38(2):168–172.
5. Watkins J, Peabody P. Sports injuries in children and adolescents treated at a sports injury clinic. *J Sports Med Phys Fitness*. 1996;36(1):43–48.
6. Flynn JM, Lou JE, Ganley TJ. Prevention of sports injuries in children. *Curr Opin Pediatr*. 2002;14(6):719–722.
7. Caine D, DiFiori J, Maffulli N. Physeal injuries in children's and youth sports: reasons for concern? *Br J Sports Med.* 2006;40(9): 749–760.

8. Brubaker CE, James SL. Injuries to runners. *J Sports Med*. 1974;2(4):189–198.
9. Hreljac A, Marshall RN, Hume PA. Evaluation of lower extremity overuse injury potential in runners. *Med Sci Sports Exerc*. 2000;32(9):1635–1641.
10. James SL, Bates BT, Osternig LR. Injuries to runners. *Am J Sports Med*. 1978;6(2):40–50.
11. Hawkins D, Metheny J. Overuse injuries in youth sports: biomechanical considerations. *Med Sci Sports Exerc*. 2001;33(10):1701–1707.
12. Roberts WO. Can children and adolescents run marathons? *Sports Med*. 2007;37(4–5):299–301.
13. Mercer JA, Vance J, Hreljac A, Hamill J. Relationship between shock attenuation and stride length during running at different velocities. *Eur J Appl Physiol*. 2002;87(4–5):403–408.
14. Shorten MR, Winslow DS. Spectral analysis of impact shock during running. *Int J Sport Biomech*. 1992;8(4):288–304.
15. Derrick TR, Hamill J, Caldwell GE. Energy absorption of impacts during running at various stride lengths. *Med Sci Sports Exerc*. 1998;30(1):128–135.
16. Hamill J, Derrick TR, Holt KG. Shock attenuation and stride frequency during running. *Hum Movement Sci*. 1995;14(1):45–60.
17. Mercer JA, Devita P, Derrick TR, Bates BT. Individual effects of stride length and frequency on shock attenuation during running. *Med Sci Sports Exerc*. 2002;35(2):307–313.
18. Mercer JA, Bates BT, Dufek JS, Hreljac A. Characteristics of shock attenuation during fatigued running. *J Sports Sci*. 2003;21(11):911–919.
19. Verbitsky O, Mizrahi J, Voloshin A, Treiger J, Isakov E. Shock transmission and fatigue in human running. *J Appl Biomech*. 1998;14(3):300–311.
20. Shea KG, Pfeiffer R, Wang JH, Curtin M, Apel PJ. Anterior cruciate ligament injury in pediatric and adolescent soccer players: an analysis of insurance data. *J Pediatr Orthop*. 2004;24(6):623–628.
21. Dufek JS, Mercer JA, Teramoto K, Mangus BC, Freedman JA. Impact attenuation and variability during running in females: a lifespan investigation. *J Sport Rehabil*. 2008;17(3):230–242.
22. Krahenbuhl GS, Williams TJ. Running economy: changes with age during childhood and adolescence. *Med Sci Sports Exerc*. 1992; 24(4):462–466.
23. Fortney VL. The kinematics and kinetics of the running pattern of two-, four-, and six-year-old children. *Res Q Exerc Sport*. 1983;54(2):126–135.
24. Schepens B, Willems PA, Cavagna GA. The mechanics of running in children. *J Physiol*. 1998;509(pt 3):927–940.
25. Cowling EJ, Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. *J Electromyogr Kinesiol*. 2001;11(4):263–268.
26. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35(10):1745–1750.
27. Derrick TR, Caldwell GE, Hamill J. Modeling the stiffness characteristics of the human body while running with various stride lengths. *J Appl Biomech*. 2000;16(1):36–51.

Address correspondence to John A. Mercer, PhD, FACSM, Associate Dean, School of Allied Health Sciences, University of Nevada, Las Vegas, 4505 Maryland Parkway, Box 453019, Las Vegas, NV 89195-3019. Address e-mail to john.mercer@unlv.edu.